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Title: SPACE SOLAR POWER FOR POWERING A SPACE ELEVATOR

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Space Solar Power for Powering a Space Elevator

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Introduction

The Space Elevator (SE) represents a major paradigm shift in space access. If the SE's promise of low cost access can be realized, everything becomes economically more feasible to accomplish in space. In this paper we describe a Space Solar Power (SSP) system capable of powering the climbers of an SE.

The initial SE will use laser power beaming from floating platforms near the SE platform [1]. This study outlines an SSP system, based near the SE at geosynchronous altitude (GEO), which powers the climbers traversing the elevator. Such a system would reduce the SE system's dependence on fuel supply from land for its power beaming facilities. Moreover, since deploying SSP systems is anticipated to be a major use for SE's, SSP's could represent an elegant solution to the problem of SE energy consumption.

SSP systems for sending usable power to Earth have been designed for well over 30 years [2]. Technologies pertinent to SSP systems are continually evolving. This slightly different application carries the added requirements of aiming the beamed power at a moving target and sending the power in a form the climbers can use. Systems considered include beaming power to the climbers directly from a traditional SSP and reflecting sunlight onto the climbers. One of our designs includes a very new technology, optical rectennas [3].

Mars SEs are conceived as having space-based power systems. Therefore, it is important to consider the problems that will be encountered in these types of applications.

SSP at GEO Considerations

In this paper it will be assumed that the SSP system is powering a 20 metric ton SE. This implies 2.4 mega-Watts (MW) of power to be beamed onto the climbers of the SE [1]. The SSP is assumed to be at GEO, approximately 36,000 kilometers (km) above the surface of the earth. Its transmitter must be articulated to keep the beam on the climber as it traverses the SE.

The three types of solar cell technologies [4] considered for this paper are optical rectenna (OR) [3], thick film photovoltaic (TFPV) and flexible photovoltaic (FPV). The simplest is the thick-film and the most advanced is the optical rectenna. Each of these technologies has its advantages.

A new technology, the optical rectenna (OR), is the most efficient and thus requires the smallest array area. The thin-film or flexible photovoltaic (FPV) solar cells have the lowest mass/unit area, but are much less efficient. The final solar cell technology to be considered here is thick-film photovoltaic (TFPV). While TFPV is less efficient than OR promises to be, it is a known and proven technology. Table 1. summarizes the array area and mass of each of these array systems.

	OR	TFPV	FPV
Area (km^2)	0.00346	0.0108	0.310
Mass (10^3 kg)	7.91	22.9	283

Table 1. Area and mass comparison of the three solar array technologies.[4]

If a single array will power multiple climbers, then many (3 to 6) transmitters will be required and the power of the array must be increased accordingly.

In the case of a solar mirror system, not only would the mirror be articulated to maintain power to the active climber, it would also need to follow the sun. It is impossible to simultaneously maintain constant, high power and illuminate the climber with one optical surface. Moreover, one would desire a focusing system to concentrate the sunlight onto the receiver area. A single optic could not accomplish these requirements. More fundamentally, a sufficiently large single mirror designed to gather 2.4 MW of solar energy would be difficult fabricate, launch and maintain its curvature, even on a massive SE. A segmented optic would be more manageable but construction on-orbit could be difficult.

If the solar reflection system is complex and consists of a receiver and transmitter then the above requirements of tracking the sun, and focusing the light onto the climber receiver can be satisfied. However, handling the high power and broad spectrum is difficult as high-power optical coatings usually work over a small range of wavelengths.

Since the dynamics of the SE ribbon are not understood in detail, it is possible the transmitter and ribbon geometry will be such that a shadow is cast across the climber receiver array. This will lower the total power on the array.

The geometry requires the receiver array to be above the payload. When power is beamed from Earth, the climber platform upon which the payload is mounted doubles as the receiver mount [1]. With a space based SSP, the payload could be suspended from the platform or a separate payload platform could be added. This option adds mass to the climber.

The spectrum of the radiation directed onto the climber is an important issue. If we employ a mirror at GEO to redirect sunlight onto the SE solar panels, the solar cells mounted on the climber would not be optimized to a specific wavelength of light. Therefore, the efficiency gained in laser power beaming by tailoring the solar cell response to the laser wavelength beamed [1] from the ground is lost.

If an SSP system is used, what type of radiation should be beamed to the climber? Solar cells convert sunlight directly into electric power. In SSP systems that are conceived to power an Earth power grid, the electrical power is converted to microwaves. This conversion is 90% efficient [2] and microwaves travel through the atmosphere without much absorption or scattering to Earth-based receiver arrays. Because of the low power density of microwaves and the difficulty of focusing these longer waves, this wavelength is not suitable for climber power. Therefore, a conversion to infrared or optical wavelengths is necessary. This conversion is less efficient than to microwaves. In fact, it probably requires the same technology as the power beaming stations on Earth – free electron lasers (FELs) feeding large (~12 meter diameter) telescopes [1]. This is a huge, expensive, and massive system to launch into space. The 12 meter telescopes and any articulation system would be the largest structures ever lifted to orbit. The FEL is essentially a particle accelerator with a wiggler magnetic field section acting as a gain medium inside a laser cavity. At the present time these are physically large, technically complex systems taking up many rooms of space and using many different technologies to make the complete system. Engineering these systems to operate autonomously and on-orbit might be a significant research endeavor in itself.

A final issue is that since the SSP is at GEO, as a climber approached GEO, the angle between the SSP transmitter and the climber receiver (a platform on the top of the climber) becomes steeper. The subtended area of the receiver visible from the transmitter would tend to zero. Thus near GEO, a GEO-based SSP could not power the climber.

One way around this is to articulate the receiver platform on the climber. This adds more mass to the climber and may not be cost effective. Batteries could carry a climber through GEO (especially since the local acceleration of gravity is near zero) but again this added mass for the sake of a small part of the trip is not cost effective.

For the few payloads that would travel beyond GEO, the receiver would be on the top of the climber once past GEO. In this case an articulated receiver or a redundant receiver would be required on the base of the climber, both cost ineffective generally.

An advantage of the SSP is that the power to the climber does not always traverse the atmosphere. The SSP system might require adaptive optics to efficiently power the climbers through the atmosphere but once above 100 km or so the SSP system is unhindered. The requirement of adaptive optics might be necessary because of the danger to the sea-based SE platforms and their personnel when the climbers are close to the earth's surface. One possibility is to use an Earth-based system to power the climbers out of the atmosphere but such redundancy may not be cost effective. There may be safety issues with the laser radiation that misses the climber receiver since it is directed toward Earth. However, if the radiation is focused at the altitude of the climber, then the higher the climber is on the SE the greater the diffusion at Earth's surface of the radiation that misses the receiver.

SSP at the End of the SE

Placing the SSP system at the end of the ribbon eliminates many of the geometry issues but presents new problems. First, the large mass of the system creates huge forces at the end of the SE since it is situated out at 100,000 km and traveling much faster than orbital velocity at that orbit [1]. Surviving such forces would dominate the design of the SE that must withstand the extra loading and not break. Thus a ribbon of much greater mass and capacity would be required to accommodate the SSP as the counterweight.

Another possibility is to base the length of the SE on the mass of the SSP system at the end. There exists a relationship between the length of an SE and the counterweight mass for a given planet [1]. If one could use a shorter ribbon, the SSP requirements could be matched to the ribbon so that it is not "over-built". A shorter SE provides less "throw" (or Δv) [1] than a longer SE, so the shorter launch system is not as capable as the longer one.

Geometry could present a problem as a climber higher on the SE could block an SSP system at the SE end from delivering power to a lower climber. Placing a 12 meter telescope (for power transmission) on a boom away from the counterweight to eliminate geometry problems would require massive structures to resist the forces experienced at the end of the SE.

Implications for the Mars SE

One conception of the Mars elevator [1] is a single package launched from an Earth SE to Mars orbit. The power system is expected to be an SSP or solar reflective unit at the end of the SE. This design carries with it the drawbacks mentioned above. The SSP system is massive and so the forces it and the SE experience on the end of the ribbon are dramatic, requiring an "over built" SSP system and ribbon to sustain them. Also, the geometric problems of blocking climbers at lower altitudes and ribbon shadowing are present as well. As in the last section, the SSP (counterweight) mass could be matched to the particular length of the Mars SE to eliminate this problem.

On the other hand, the colonization of Mars is a great undertaking and a Mars elevator would be a vital link in the transportation system. It is possible that overbuilding the cable, downsizing the SSP system thereby running the climbers more slowly, overbuilding the SSP mechanical assemblies to withstand the large forces and running one climber at a time are quite reasonable trades in the overall systems engineering trade space.

As colonization progresses, Martian SEs might be built with their power stations on the Martian surface to eliminate the drawbacks of the space-based SSP. Moreover, an SSP system at "Martian-stationary" orbit could provide power for a Martian power beaming system by beaming microwave power to a receiving system on the ground as in proposed terrestrial SSP systems.

Conclusions

Although SSP systems are capable of generating the power required to operate an SE climber, geometrical and power delivery to the climbers has many problems. Reflective energy supply systems must surmount even more problems than SSP systems. SE systems designed to accommodate a very large counterweight could be feasible in certain applications although their shorter length would limit the Δv these launchers could provide. In certain environments SSP systems may power SE climbers such as the initial Martian SE.

References

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